Implementation of a patient specific model for the calculation of glenohumeral subluxation

Author: Sveva Fornari
Supervised by: Yasmine Boulanaache and Alexandre Terrier
Professor: Dominique Pioletti
Laboratory: Laboratory of Biomechanical Orthopedics, Ecole Polytechnique Federale de Lausanne, Lausanne, Switzerland
June 8, 2018

Introduction: Total Shoulder Arthroplasty is a well-established surgery for restoring comfort and function to the arthritic shoulder. Among the different surgical options this procedure appears to provide the most rapid and complete reestablishment of the normal conditions. Still, there is a high failure of the implant after the surgery (5- to 10- year failure rates for is up to 10% [1]). This is mainly caused by luxation due to aseptic glenoid loosening, associated with off-center loading.
Method: In this study, a new method for the prevision of subluxation after total shoulder arthroplasty is developed. The final goal of this study is to prevent and anticipate subluxation's risks thanks to a patient-specific model for the calculation of subluxation. The model is developed based on pre-operative and post-operative CT-scans of patients that already underwent the surgery at the CHUV (The Lausanne University Hospital). A comparative study between subluxation's calculation with normal and overcorrected implant is undergone. The design of this last overcorrected implant (still not commercialized) is developed to reduce the subluxation.
Results: A new end-to-end method has been developed for the measurement of subluxation. The results obtained during this first study do not confirm about the potential of this new implant, but encourage to get deeper into the model development, both for the FE-model and the implant design to find a new design able to reduce the post-operative subluxation.
Conclusion: The new developed tool for the prediction of subluxation is very promising in the subluxation's risk prevention after TSA. Still, efforts need to be done on the model's development to obtain better results for the possible future commercialization of new overcorrected implants.

Contents

1 Background

1.1 Total Shoulder Arthroplasty for humeral subluxation

Total shoulder replacement arthroplasty (TSA) is a common surgery for restoring comfort and function to the to the arthritic shoulder. Glenohumeral (GH) osteoarthritis is in fact a common source of pain and disability that affects up to 20% of the older population. Its primary cause is the damage to the cartilage surfaces of the glenohumeral joint.

During TSA, the humeral head is replaced by a smooth metal ball fixed to the arm bone (humerus) by a stem that fits within it. The glenoid is resurfaced with high-density polyethylene prosthesis (cf. Figure 1).

Among the different surgical options this procedure appears to provide the most rapid and complete improvement in comfort and function for shoulders with arthritis.

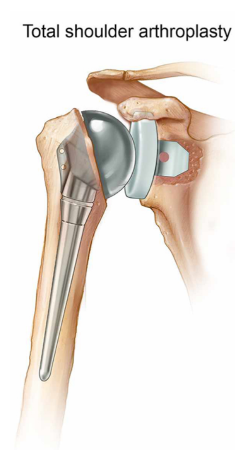


Figure 1: TSA

Nevertheless, patients presenting some preoperative shoulder's problematics, as humeral subluxation, have reported much worst results [2]. In fact, it has been remarked that often this kind of patient present some complications after the operations, as a recurrence of the subluxation and therefore a risk of wear of the implant [3] [4].

Humeral subluxation is defined as a partial or incomplete dislocation of the humeral head from the glenoid cavity. To give a quantitative measurement of the subluxation is not always easy: Papilon and Shall defined the glenohumeral subluxation as the percentage oh humeral head offset from the glenoid axis relative to the humeral head diameter [5].

1.2 Finite Element for shoulder modeling

The Finite Element method is a very powerful tool to analyze, predict and discuss in a simple manner complicated loading situations, often implying complex geometries, like the shoulder's one. For this study, a patient-specific FE model for the shoulder is developed in order to discuss about the subluxation of the patient under specific loading conditions.
The model is developed based on CT-scans of the patient to reconstruct the geometry of the shoulder, and in particular the area surrounding the glenoid cavity's.

1.3 The solution brought by collaboration between EPFL and the CHUV

A collaboration between the Laboratory of Biomechanical Orthopedics (at EPFL) and the CHUV (Centre Hospitalier Universitaire de Lausanne) has been instaured to face the problem of subluxation after TSA. The engineers and the surgeons come out with one possible solution that is currently under study: the design of augmented implants for the glenoid resurfacing. The over-corrected implant intends to realign the humerus with the scapula, as well as to prevent posterior humeral head translation.

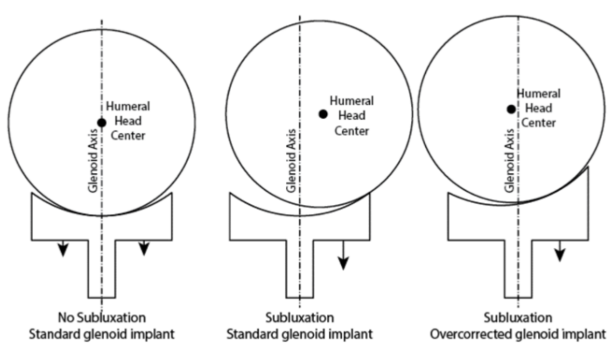


Figure 2: How to reduce subluxation with the new overcorrected implants

1.4 The previous results of other projects

This study is based on a previous study made by Sandro Bergamin during his Master Thesis Project at the LBO (The Laboratory of Biomechanical Orthopedics) at the EPFL, in Lausanne (Switzerland), and in collaboration with the CHUV (Centre Hospitalier Universitaire de Lausanne). In his model, Sandro Bergamin showed that the over-corrected implant was able to avoid posterior humeral head subluxation and extensive posterior edge loadings. Still, he underlined at the end his study that further limitations of this augmented implant should be considered, as the material added to the implant that may overload the shoulder. Also, the study was not conducted on a long-term perspective: the humeral anterior alignment might increase the probability of anterior edge loading and critical anterior subluxation[6].

1.5 Aim of the study

This study is intended to develop a new method for the measurement of subluxation after the implant positioning. For that, a FE-model is developed from CT-scan of patients.

The results obtained from the model aim to help the surgeon and influence his choice for the choice of the implant. It is the reason why, the accuracy of the model is crucial, as well as the repeatability of the study from a patient to another, in order to obtain reliable and comparable results. Therefore, an important part of the study aims also in developing a protocol as clear as possible to allow in future cases to reproduce the same study as developed in this case.

Nevertheless, sources of error may come from the incorrect segmentation of the shoulder, or by the difficulty in reproducing the in-vivo biological situation. Moreover, the material properties (derived from the CT-scan density parameters) may not be 100% accurate, and the material law used to characterize the elastic properties of the bone may also bring some inaccuracies. It is important to underline these factors of uncertainty in order to examine with criticism the output of this study.

2 Method

To create a Finite Element Model (FEM) for the calculation of subluxation, several steps and different software were required (Figure 3). The first part of the model is concentrated on the implementation of a patient-specific model of his right shoulder. The second part is focused on the development of a script for the calculation of subluxation. This last script is developed both in Python and Matlab.

The general working flow is presented in Figure 3. The model is developed thanks to four different softwares: Amira (Visual Imaging GmbH), Geomagic Design X (3D Systems), SolidWorks (Dassault Systems) and Abaqus (Dassault Systems).
Further details of the steps are given in the following paragraphs.

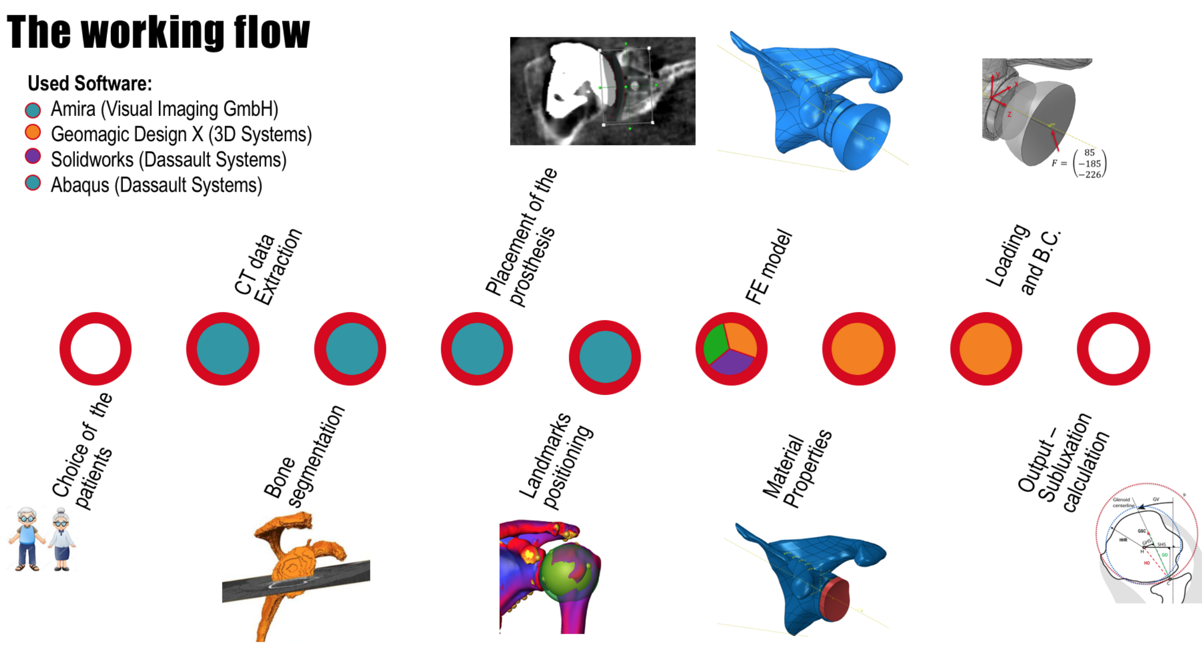


Figure 3: The major steps for the development of the 3D patient-specific model

2.1 Creation of the 3D Model

2.1.1 The scapula segmentation and smooting

The model of the scapula is based on patient computer tomography scans. The images are provided by the Centre Hospitalier Universitaire de Lausanne (CHUV). For this study, both pre-operative and post-operative CT-scans are provided by the CHUV. The post-operative scans have in general a less good quality due to the presence of metallic parts (in the implants). Therefore, the segmentation of the scapula is done thanks to the pre-operative CT-scans, while the positioning of the implant (see Section 2.1.2) is done thanks to the post-operative CT-scans.

To generate the 3D bone surface, the 3D preo-operative CT-scan is sectioned into subsequent 2D images: from these images, the cortical bone contour is segmented with the help of the density informations provided by the CT-scan and the obtained segmentations are interpolated. The segmentation process is semi-automated. The idea of this semi-automated segmentation is to automate the contour detection of the cortical bone thanks to density informations extracted from the CT-scans and after that eventually refine manually the contour in regions where the automated process failed, taking

particular attention to the region close to the glenoid cavity, as it is the region of interest for the FE-model.
It is a semi-automated process as the cortical bone contour segmentation is automated but the trabecular bone extraction is done by surface shrinking. In fact, for the trabecular bone extraction, having a look at the CT images, Terrier et al. [7] concluded in their study that the cortical bone has a mean thickness of approximatively 3mm. Therefore, in order to obtain the trabecular bone, the bone is shrunk 6 times (because 1 pixel corresponds to 0.49 mm). The cortical bone is obtained subtracting the trabecular bone to the entire bone.

Once the segmentation of the cortical and the trabecular bone are computed, the surfaces are exported in Geomagic for surface smoothing and generation. The trabecular surface and the cortical external surface are treated separately in this steps, and will be assembled in a second time.

2.1.2 Implants design and positioning

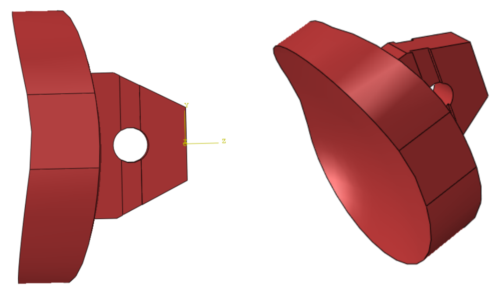


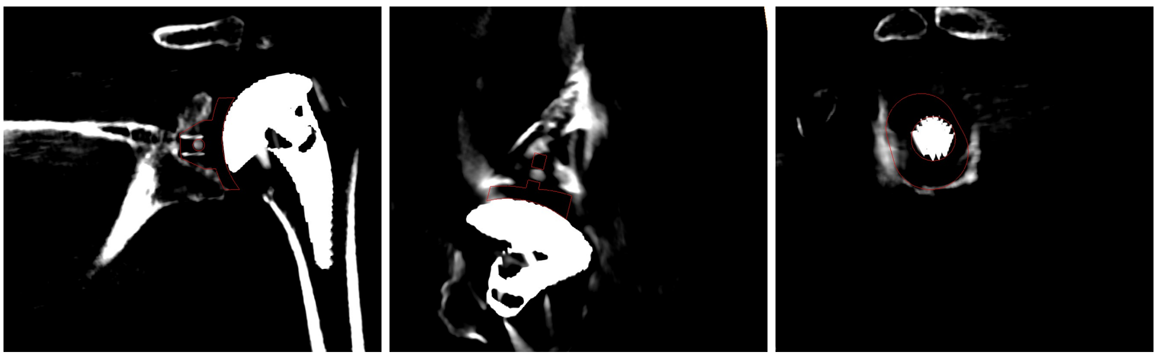
Figure 4: Original augmented implant - *Name of the implant: PAG 15 M40 left*

The choice of the appropriate implant for the patient is done by the surgeon, and reported to the laboratory. For this patient, an augmented implant is chosen due to the particular geometry of the glenoid cavity of the patient. The implant are provided by Wright Medical (Tornier Inc, Bloomington, USA). In particular, the implant chosen for this patient is the PAG 15 M40.

The implant positioning is a delicate step in the development of the model. For this study, the implant position is defined thanks to a postoperative CT-scan of the patient. The intent is in fact to place the implant at the exact location where it has been positioned during the surgery, which is not always the position expected by the surgeon before the surgery.
In Figure 5, the three principal planes for the implant positioning are shown. A multi-thresholding is applied to better distinguish the implant from the bone (1000 HU) and the bone from the surrounding medium (150 HU). In red, the projection of the implant on the planes is drawn, to allow for a better visualization of the implant positioning. In Figure 15b, one can distinguish for example the cement at the center of the posterior hole of the implant, while in Figure 15a, one clearly see the hole of the implant in the scan, appearing as a whiter dot.
The accuracy of the placement of the prosthesis is not estimated quantitatively, but qualitatively, thanks to a combination of the information provided by the three orthogonal planes, it seems that the placement of the prosthesis is precise and reliable.

Once the implant is positioned correctly, the post-operative scan has to be aligned over the pre-operative one. For this step, an automated segmentation of the post-operative CT-scan is done, by keeping just the medial part of the scapula into account. The lateral part, close to the glenoid, presents

generally more artifacts caused by the metallic humeral head. Moreover, as the preo-operative and post-operative CT-scans have been computed at different times, the humerus is not positioned at the same place in the two cases, so a consideration of this bone in the surface alignment would lead to an error in the alignment process.
The transformation resulting from this alignment is applied finally to the implant, which is positioned at this time on the post-operative scans, to place it over the pre-operative scan.
This process of alignment and positioning is described in Figure 6. The three steps of the implant positioning are clearly detected: the first one correspond to the implant importation in Amira, the second one to the implant positioning on the post-operative scan and the last one on the implant positioning over the preoperative scan.



(a) Frontal plane (b) Sagittal plane (c) Transverse plane

Figure 5: Positioning of the implant based on the postoperative CT-scans thanks to the principal planes

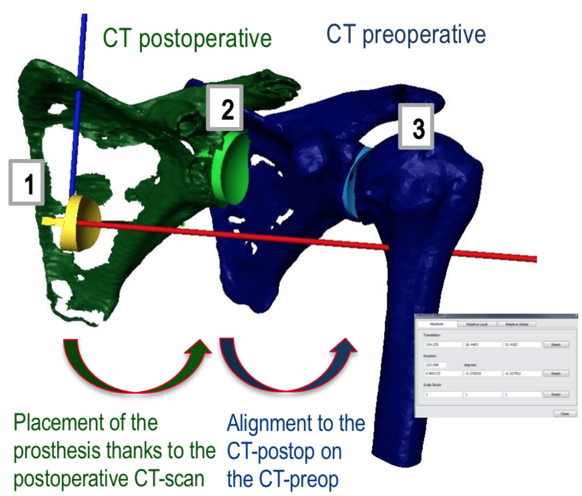
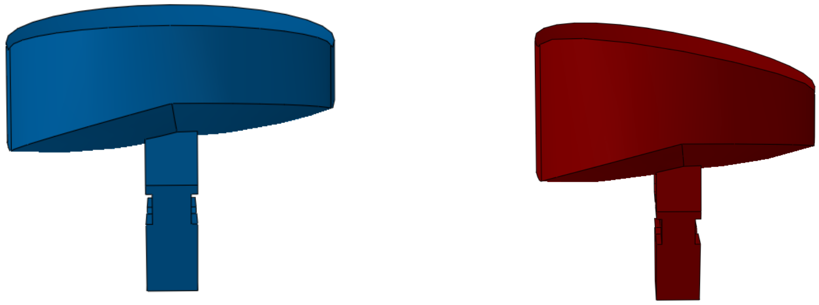


Figure 6: Alignment of the post-op CT over the pre-op CT and placement of the prosthesis process

In Figure 7, the over-corrected implant is displayed. The implant is corrected at the posterior (distal) level of the implant to force the humerus to be better aligned at the center of the glenoid. For the positioning of this implant, as the medial part of the implant (the one in contact with the glenoid) is kept the same, the same alignment is done for this implant. Therefore, the same transformation applied to original implant is applied for this over-corrected one.



(a) Original Implant (b) Over-corrected implant

Figure 7: Additional overcorrection for subluxation reduction

2.1.3 Component assembly

The components are finally assembled in Solidworks for further exportation in Abaqus. One may be aware of the fact that in Amira, 3D rotations are defined as a rotation around a certain axis. Therefore, in Solidworks, this same rotation is applied by creating the axis of rotation and rotation the implant around it.
Thus, the total transformation applied to the implant for the right positioning (transformation from point 1 to point 3 in Figure 6) is extracted from Amira and applied to the implant again in Solidworks. The glenoid surface is then modified thanks to the Outil (Figure 8) to have a perfect match between the implant and the bone (the Outil is suppressed right afterwards). This operation reflect the operation done by the surgeon before the placement of the prosthesis and is done by creating surface interactions between the implant and the cement and then the cement and the Outil for the correct positioning of the cement and the Outil.
The humeral head is designed directly in Abaqus.

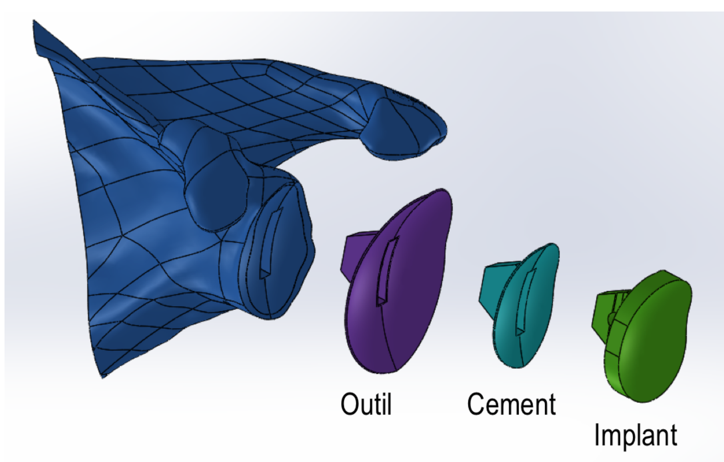


Figure 8: Solidwork's assembly

2.2 The FE Model

Once the 3D Model has been implemented, the FE model is developed in the Abaqus software. In what follows, the materials, boundary conditions and applied loads are described.

The humeral head is designed in Abaqus as a rigid half sphere. This last is designed just for the application of the load, and will not be part of the FE study.

2.2.1 Material properties

For the material properties, all the components are assumed to follow a linear elastic behavior. Moreover, we assume the bone to be homogeneous and isotropic. In Table 1 the properties of the materials are listed. In particular, the elastic properties of the bone where extracted from literature studies ([8] [9]).

	Young's Modulus [MPa]	Poisson ratio [-]
Trabecular bone	500	0.3
Cortical bone	11500	0.3
Cement	2000	0.23
Implant	720	0.4

Table 1: Material Properties for the model. The materials are considered homogeneous, linear, isotropic and elastic

2.2.2 Surfaces interactions

Tie constraints were applied between the implant and the cement as well the cement and the bone. The contact between the humeral head and the glenoid was modeled as a standard surface-to-surface contact with allowed finite sliding. A friction was added for the tangential behavior between the humeral head and the implant, of a value of 0.2, as reported in the study of Xiong et al. [10].

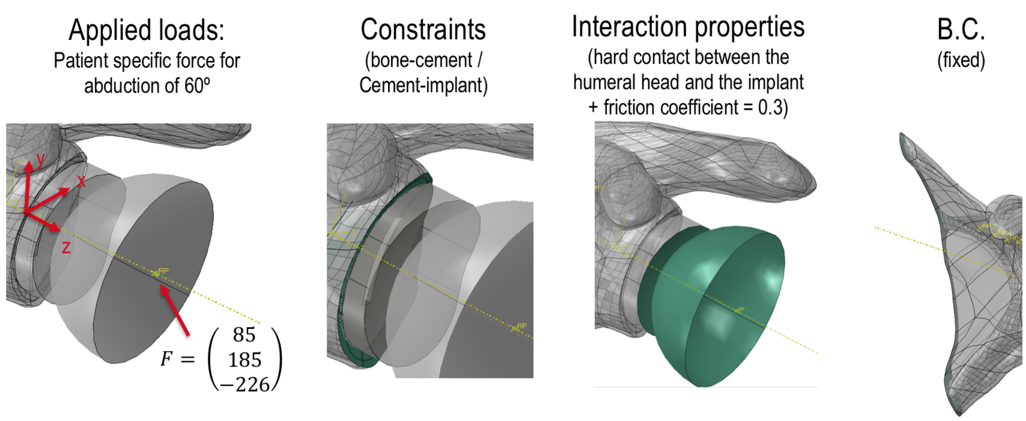


Figure 9: Surfaces interactions and boundary conditions

2.2.3 Boundary conditions and applied external forces

For this study, the scapula is fixed at the end surface at the proximal side (cf Figure 9).
A patient specific load is applied at the center of the humeral head, considered as a solid undeformable body, to mimic an abduction of 60°. (cf Figure 9).
The humeral head center is constraint to move only in the direction parallel to the scapula plane (fixed in the proximal/distal direction).

2.2.4 Mesh properties

For the mesh properties, an approximate global size of 3mm is used for the mesh generation. This last result comes from a recent study done at the LBO [11]. In this study, a sensitivity analysis of a patient specific finite element model for shoulder arthroplasty was developed, following the same guidelines as for this project. Therefore, no further mesh sensitivity has been performed for this study as it is assumed that the results would have been very similar to these lasts.

2.3 Method for the measurement of the subluxation

For the calculation of the glenohumeral subluxation, the definition presented by Terrier et al. [12] is employed. In this study, the authors argued about the importance of 3D detection of the subluxation, insisting on the fact that a 3D measure of the subluxation would lead to more valuable information for decision making during TSA. In fact, at this time, the subluxation is generally measured in 2D, relative to the glenoid face.

The subluxation can be generally calculated in terms of glenohumeral subluxation (GHS) or scapulohumeral subluxation (SHS) . The 3D glenohumeral subluxation is defined as the relative distance between the humeral head center and the glenoid center projected onto a plane perpendicular to the glenoid centerline, whereas the 3D scapulohumeral subluxation is defined with the same distance but projected onto a plane perpendicular to the scapular axis.
In this study, we focus on the glenohumeral definition for a quantification of subluxation to follow the procedure of laboratory.

For the calculation of glenohumeral subluxation, three reference points needs to be extracted from the simulation:

- The glenoid center, or the closet point between the mean of the extracted glenoid surface and all the points of the extracted glenoid surface, C.
- The center of the sphere fitted on the glenoid surface (the glenoid sphere), GSC.
- The center of the humeral head.

The two first reference points are the ones describing the glenoid centerline, and are considered to be fixed during the simulation. Therefore, they were extracted in Amira thanks to a feature extraction performed on the scapula. (cf. Annexe of Section 8) The center of the glenoid sphere was instead extracted thanks to an implemented python code after the simulation in Abaqus, to analyze the shift in the position of the humeral head after the application of the patient specific load for a 60° abduction. With these data extraction, the GHS can be defined as thanks to the humeral Head Offset (HO) and the Glenoid Sphere Center offset (GO) as follows:

$$HO = H - C$$

$$GO = GSC - C$$

$$GHS = HO - (HO \cdot \frac{GO}{\| GO \|}) \cdot \frac{GO}{\| GO \|}$$

The glenohumeral subluxation index (GHSI) is expressed as the GHS normalized over the diameter of the humeral head:

$$GHSI = \frac{\| GHS \|}{2 \cdot HHR}$$

In Figure 10, the definition of the GHS is describe with the help of a schema.

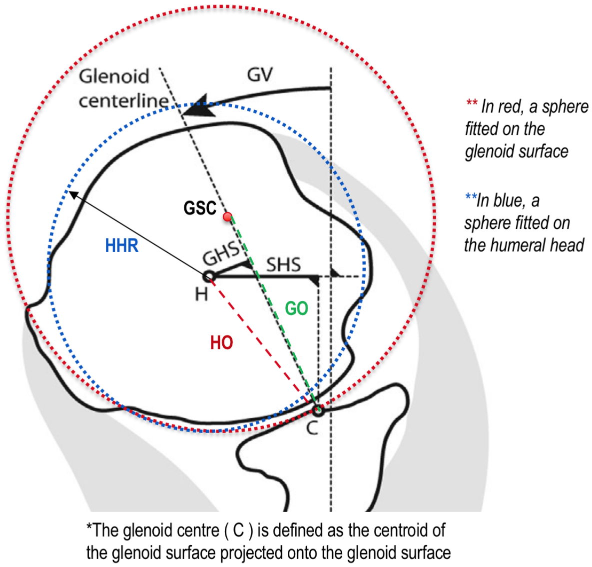


Figure 10: Glenohumeral Subluxation definition

3 Results

A short overview on the obtained results is presented in this section. The contact pressure of the movable humeral head on the fixed implant is plotted in Figure 11. One can remark that with the new overcorrected implant, the point of contact is more central than with the normal implant, and the pressure is better distributed (lower maximal pressure).
In Figure 12, the off-centering of the humeral head with respect of the scapula is plotted. One remark, that as the model has imposed, the center of the humeral head doesn't move laterally. The effect of the overcorrected implant results in a rotation of the humeral head and a reduced displacement of the humeral head in the direction of the scapula.
In Table 2, the results of the glenohumeral subluxation's calcualtion in form of a glenohumeral subluxation's index (GHSI) are displayed. The GHSI values are very similar for the original and overcorrected implant.
In what follows, a brief discussion of these obtained results will be performed.

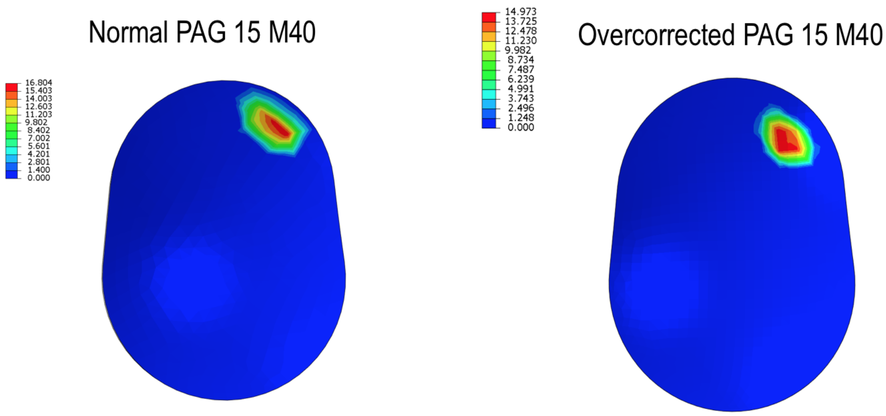
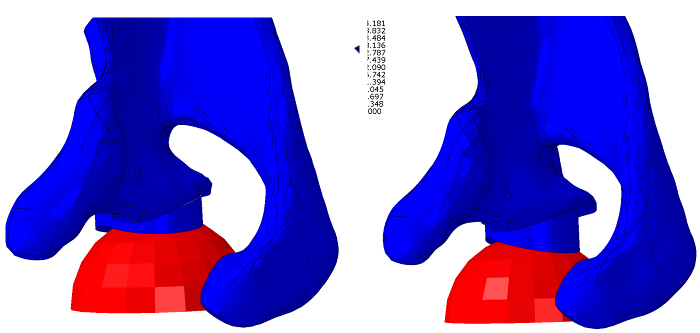


Figure 11: Contact pressure for the normal and overcorrected implant

	Original Implant	Overcorrected Implant
GHSI	6.76%	7.52 %

Table 2: Results of the Glenohumeral Subluxation calculation



(a) Original implant (b) Overcorrected implant

Figure 12: Off-centering of the humeral head with respect to the scapula after the application of the patient specific force

4 Discussion

During this study, a new method for the calculation of subluxation has been developed with the intent of automating the process of calculation of subluxation for the prevision of subluxation after the total shoulder arthroplasty. The method is to be used on patient specific models with the final scope of trying to reduce the high failure rate due to the off-center loading associated with subluxation. Indeed, thanks to this method, the surgeon, in collaboration with the engineers, will be able to predict more accurately subluxation and try to develop a more specific implant for the patient to avoid post-operative problems. This tool can indeed be used on different implants and different patients.
Also, being went through an end to end process during this study, from the extraction of the scans before the surgery to the final prediction of subluxation after surgery, a more general overview on the process has been obtained and the robustness as well as the validity of all the steps has been assessed. The process is in fact still not automated at 100%, requiring therefore particular attention during its processing.
Steps as the implant positioning or the bone segmentation are to be done with particular attention, as they are patient-specific and can present challenges proper to the patient situation. Those steps are also difficult to validate. For the bone segmentation for example, a semi-automated technique has been used but totally manual segmentation has been proven to show better results (internal study to the LBO done by Raphaelle Peyraud). Still, this last technique is much more time consuming and can lead to more complicated geometries to mesh, as the trabecular bone is not anymore obtained by surface shrinking but by manual segmentation, leading to very thin areas with complex surfaces, that can result in complicated volume meshing. With the semi-automated method we therefore loose in accuracy but gain much in time and simplicity. The implant's positioning is another step difficult to validate, as this positioning is done just thanks to a combinations of informations obtained from three orthogonal planes, and is highly dependent on the quality of the postoperative CT-scans, which often due to ethical reason (trying to reduce as much as possible the doses for the post-operative CT-scans as less informations needs to be extracted from them) but also the presence of metallic parts has a bad quality with respect to the pre-operative ones. Still, one idea for the validation of the implant's positioning would be to make a rapid segmentation of the implant thanks to the posteoperative CT-scan and then quantitatively define the matching between the two surfaces (for example thanks to the alignment tool in Amira it is possible to extract the quality of the alignment between two surfaces).

Now that the process has been verified in its integrity, some further improvements could be considered to increase the accuracy of the final results.

For example, the bone has been considered to be homogeneous, which is not the case. This problem has already been faced in the LBO, and the idea is to introduce the inhomogeneity by the density-measurements in the CT-scan. In fact, the bone mechanical properties are directly related to the bone mineral density related to the grayscale (HU) values measured in the CT-scans.

In addition, the loading conditions and the constraints applied to the model could be verified to be sure that they reflect the in vivo conditions. In this study, the humeral head has been constraint to move on the axis passing through the center of the implant, but this choice hasn't been justified. This is probably also the reason why the glenohumeral subluxation index obtained is not as expected (higher GHSI for the overcorrected implant). Also, this method could be use as one the methods to assess the validity of the overcorrected implant geometry. In fact, in this study it has been tried to evaluate the subluxation after the implant has already being implanted, but one could imagine using this method as a preoperative test for the implant. Still, the information about the post-operative scan would in this case lost, so the implant positioning's method would have to be reconsidered.

A last remark is that this protocol has been applied just on a patient for the moment, so it would also be interesting to verify its robustness by applying it to other patients, and other implants.

5 Conclusion and further possible improvements

The new method for calculation of subluxation that has been developed during this study has demonstrated to be an useful tool for postoperative subluxation prediction. This tool could be used for implant's design optimization as well as for implant's positioning optimization with the aim of reducing the high postoperative implant's failure proper to total shoulder arthroplasty. Implant's failure after TSA is in fact a too common consequence in the today's surgery and lots of efforts still need to be done to improve this situation.

Still, the process described in this report for the calculation of subluxation is long and not optimized in terms of automation. With the emerging new machine learning tools for example, it would be interesting in the future to automatize more some steps, as for example the segmentation or the implant's placement.

To conclude, this study proved again that tools like numerical simulation can be very useful in decision making for the surgeons. There is in fact a true benefit in the collaboration between engineers and surgeons for the enhancing of the patient's well being. Also, with the new industry 4.0 and new manufacturing tools like 3D printing, the solution that are research for the patient are always more personalized and patient-specific. There is therefore a real day by day rising interest in the development of these new patient-specific models in the biomedical field.

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6 Appendix: E2E Protocol

Amira:

- Follow the Steps suggested by Alexandre Terrier: Abaqus shoulder model for abduction (SOP)
- Export a label “Bone” for the bone and a label “Trabecular” for the trabecular bone. The substraction of the two labels will be done afterwards in Solidworks to ensure a proper surface contact between the two and avoid any possible voids.
- For the placement of the prosthesis, some indication about the choice of the planes are described in Figures 14 and 15
- For the surface alignment, be sure to exclude the artifacts due to the presence of the metallic implant and to the low quality of the CT-scan. For example, the proximal part of the scapula should not be considered
- Once the implant has been positioned on the preoperative CT, extract the total transformation applied to the implant for its positioning. This transformation can be used by the getTransform command on the Amira command window, or thanks to the transform Editor in Amira. (Fig. 16)
- Once the positioning and the segmentation is done, the last step is to do the landmarks' positioning. At this aim, a very precise script has already been developed. With this landmarks, the code scapula_addmeasure should be run to extract the desired "Reference" file necessary for the subluxation calculation. In this file in particular, the glenoid centerline coordinates are included.

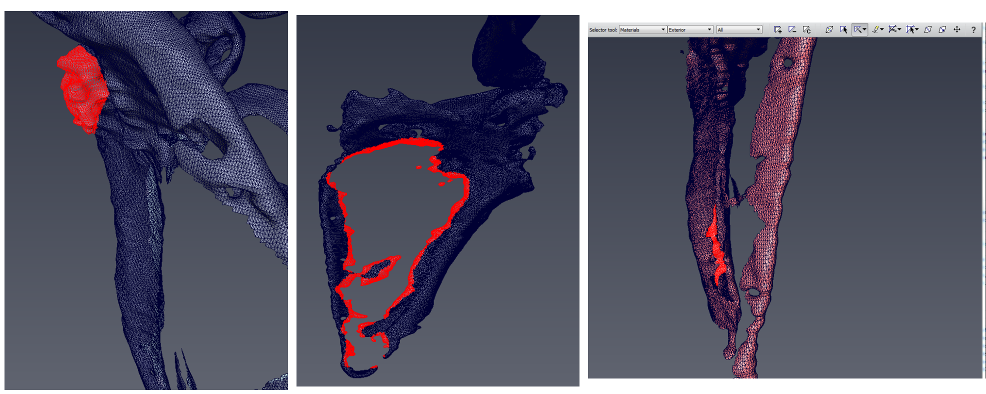


Figure 13: Surfaces to be removed from the CT postop for the surfaces alignment. *On the right, a typical artefact's due to the presence of the metallic part. On the center and right the surfaces are closed automatically by Amira because of lack of information on the central part. Still, this closing is not correct.*

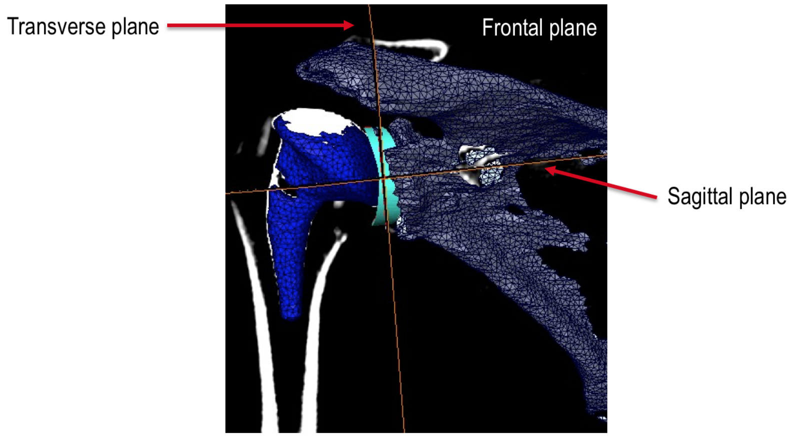
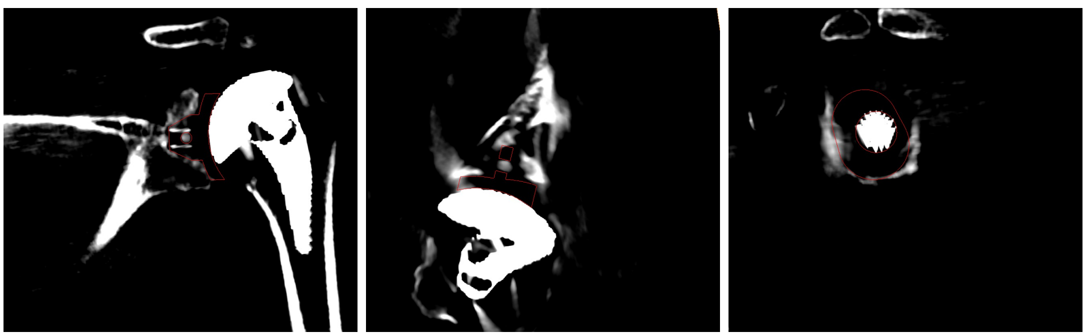


Figure 14: Definition of the reference planes for the placement of the prosthesis



(a) Frontal plane (b) Sagittal plane (c) Transverse plane

Figure 15: Positioning of the implant based on the postoperative CT-scans thanks to the principal planes

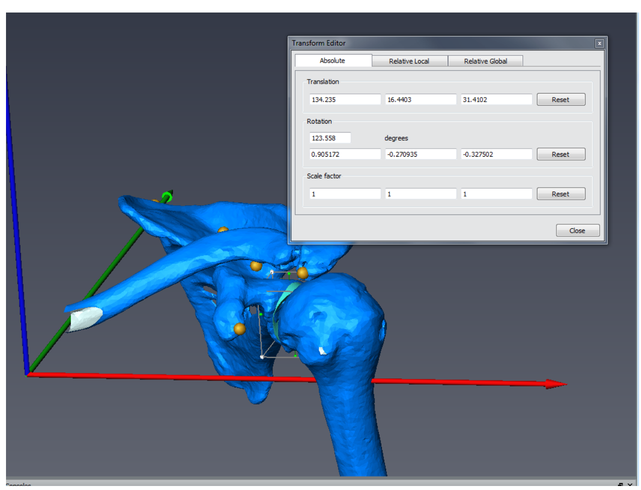


Figure 16: Transformation to be applied to the implant for the correct positionning over the scapula

Geomagic:

- Follow the Steps suggested by Alexandre Terrier: Abaqus shoulder model for abduction (SOP)

Solidworks:

For the assembly in Solidworks, the Amira's reference frame is used (the default one when importing the parts). It is important therefore to keep the bone fixed with respect to its coordinate frame. This will help a lot in the transformation and placement, as well as for the reference points import, which are defined in fact in the Amira Reference Frame.

- Import the two .sat files exported from Geomagic.
- Subtract the trabecular bone to the total bone (cortical label) to obtain the cortical bone. This is done thanks to the boolean subtraction tool. Be careful that this is possible only if the two surfaces are closed. If it is not the case, close the surfaces before. Also, try to move the trabecular on the cortical, keeping therefore the cortical fixed. This is necessary for the placement of the prosthesis.
- Create an assembly composed of the trabecular bone, the cortical bone, the implant, the cement and the tool.
- For the placement of the prosthesis, import the transformation extract in the last step of Amira (Figure 16). Be careful that in Amira the transformation is defined as a translation + a rotation around a certain axis. To apply this transformation in Solidworks, create the axis of revolution (between the origin of the reference coordinate system and the point defined in the Rotation section) and then rotate by the angle (here 123 °). Once the implant is rotated it can be easily translated to. This operation should be better done directly on the part and not on the assembly.
- Once the implant has been positioned on the scapula, follow the steps described in the SOP Protocol (Abaqus Shoulder Model for Abduction, page 5 of 17). This steps include the cement placement and the cutting of the glenoid surface interfering with the implant thanks to the tool.
- For the positioning of the overcorrected implant there are two possible solution: the first one is to recompute the same transformation done for the normal implant, and the second one is to create more easily 3 surface matches between the old and the overcorrected implant in the Solidworks' assembly.

Abaqus:

The model is now ready for exportation in Abaqus. For this step, the SOP Protocol (Abaqus Shoulder Model for Abduction) is again very precise. The most convenient thing to do is to copy the open the Abaqus folder of an existing model (included in "lbovenus:/shoulder/method/abaqus/example") and try to do the same. Still, there are some new things that should be done for this specific case:

- Create a Field Output Request for the extraction of the coordinates of the Humeral Head Center. This can be founded in the Volume/Thickness/Coordinates category.
- In the Assembly, create a Set for the humeral head center coordinate (this point should be generated automatically when the solid semi-sphere of the humeral head is created). This set is important for the feature extraction afterwards thanks to the Python code.

Subluxation calculation

In this last section, the idea is to import the results obtained both in Amira and Abaqus and to execute a Matlab code (see Section 8) for the calculation of subluxation. Normally, there should be 3 files ready to be exported:

- The Reference_P###.dat file extracted from the add_measure script generated thanks to the placement of the Landmarks in Amira
- The CooHumeral.rtp file for the coordinates of the humeral head after the calculation in Abaqus
- The CooHumeral_overcorrected.rtp file for the coordinates of the humeral head in the case of the overcorrected implant after the calculation in Abaqus

Once the needed files are gathered, follow the next explanations:

- Two folders have been created to gather these informations: Generated_AMIRA_TCL_Scripts for the Reference and Generated_Pyhton_subluxation_files. This step is not necessary, be careful in the Matlab code to modify these paths if needed.
- The Matlab code create is a function called subluxation_calculation(HHRadius). The argument HHRadius corresponds to the radius of the humeral head created in Abaqus. This value should be added manually to the Matlab code.
- Run the Matlab code. The output values for this function are: GHSI (the Glenohumeral Subluxation Index), GHSI_overcorrected (the Glenohumeral Subluxation Index for the overcorrected implant) and some coordinates. These coordinates are placed in the output for a matter of visualization. It could be in fact interesting to plot the results and analyze them (see the Appendix in Section 9).

7 Appendix: Python code for the Humeral Head coordinates extraction

In this script, a Python code for the humeral head coordinates extraction is developed. At this aim, before the Simulation, in the Assembly a Set called "SET-7-HEAD_CENTER" is created. Also, a Field Output Request should be created, including the COORD (Current nodal coordinates) option, in the Volume/Thickness/Coordinates category.
myBoneName refers to the name of the humeral head part in Abaqus, and should be written in capital letters.
The results are written in an output file called "CooHumeral.rtp", ready for use in Matlab.

```
 #Python routine that let to automate the results processing of a movement simulation
import os
import math
import numpy
import sys
from numpy import zeros
from odbAccess import *
from abaqusConstants import TRUE
from abaqus import *


# Change names here
odbname = ('P411_2.odb')
myOdb = openOdb(odbname)
myStep = myOdb.steps['PSForce']
myBoneName=('HUMERAL_HEAD2-1')
mySetName=('SET-7_HEAD_CENTER')

#-------------------------------------------------
#Frame of interest and its values
#-------------------------------------------------
myFrame = myStep.frames
i=0
for number in myFrame:
    i=i+1
i=i-1
myFrame = myFrame[-1]   #takes the last increment

myBone= myOdb.rootAssembly.instances[myBoneName]
myDisplacement = myFrame.fieldOutputs['U']

myDisplacementBone = myDisplacement.getSubset(region= myBone)
myDisplacementBone1 = myDisplacementBone.getSubset(position = NODAL )
myPrinBone=myDisplacementBone.values


# Get the displacement

myOutputDisplacement = open('DispHumeral.rpt', 'w')
i=0
for values in myPrinBone:
    i=i+1

NodeLab=zeros(i,'int')
Disp1=zeros(i,'float')
Disp2=zeros(i,'float')
Disp3=zeros(i,'float')
DispMag=zeros(i,'float')
```

```
Coo1=zeros(i,'float')
Coo2=zeros(i,'float')
Coo3=zeros(i,'float')
CooMag=zeros(i,'float')

for ii in xrange(i):
    NodeLab[ii]= myPrinBone[ii].nodeLabel
    Disp1[ii]=myPrinBone[ii].data[0]
    Disp2[ii]=myPrinBone[ii].data[1]
    Disp3[ii]=myPrinBone[ii].data[2]
    DispMag[ii]=myPrinBone[ii].magnitude

    line_file='%i %.5f %.5f %.5f %.5f\n' %(NodeLab[ii], Disp1[ii], Disp2[ii], Disp3[ii], DispMag[ii])
    myOutputDisplacement.write(line_file)


myOutputDisplacement.close()


# Get the coordinates

myCoordinates = myFrame.fieldOutputs['COORD']

myCoordinatesBone = myCoordinates.getSubset(region= myBone)
myCoordinatesBone1 = myCoordinates.getSubset(position = INTEGRATION_POINT )
myCooBone=myCoordinatesBone.values


myOutputCoordinates = open('CooHumeral.rpt', 'w')
i=0
for values in myCooBone:
    i=i+1

Coo1=zeros(i,'float')
Coo2=zeros(i,'float')
Coo3=zeros(i,'float')
CooMag=zeros(i,'float')

for ii in xrange(i):

    Coo1[ii]=myCooBone[ii].values[0]
    Coo2[ii]=myCooBone[ii].values[1]
    Coo3[ii]=myCooBone[ii].values[2]
    CooMag[ii]=myCooBone[ii].magnitude


    linecoo_file='%i %.5f %.5f %.5f %.5f\n' %(NodeLab[ii], Coo1[ii], Coo2[ii], Coo3[ii], CooMag[ii])
    myOutputCoordinates.write(linecoo_file)

myOutputCoordinates.close()
```

8 Appendix: Matlab code for the calculation of subluxation

```
function [GHSI, GHSI_overcorrected, Glenoid_Center,GC_Sphere_Center,HC,HC_overcorrected]
= subluxation_calculation(HHRadius)

close all
%% This function allows to calculate the GHSI thanks to the importation of the References points obtained
%% with the matlab code already generated scapula_addmeasure and the output 'References' obtained with it.

%% The humeral head center coordinates are imported thanks to the Python script humeral_head_abqoutput and
%% humeral_head_overcorrected_abqoutput.

%% These two files are placed in their corresponding directorines (directory_Amira and directory_Abaqus).

directory_Amira ='E:\Generated_Amira_TCL_Scripts\References\';
directory_Abaqus='E:\Generated_Python_subluxation_files\';
filename = strcat(directory_Amira,'References_P411.dat');
delimiter = ',';
formatSpec = '%s%s%s%[^\n\r]';
fileID = fopen(filename,'r');
References = textscan(fileID, formatSpec, 'Delimiter', delimiter,  'ReturnOnError', false);
References=[References{:}];
fclose(fileID);

HC_filename= strcat(directory_Abaqus,'CooHumeral.rpt');
HC_overcorrected_filename= strcat(directory_Abaqus,'CooHumeral_overcorrected.rpt');
HC=load(HC_filename);
HC_overcorrected=load(HC_overcorrected_filename);

if HC_overcorrected(1,1)==1
   HC_overcorrected=HC_overcorrected(1,2:4);
else
    HC_overcorrected=HC_overcorrected(1,1:3);
end

if HC(1,1)==1
   HC=HC(1,2:4);
else
    HC=HC(1,1:3);
end
%% Calculation of subluxation

for i=1:3
Glenoid_Center(i,1) = str2double(References{12,i});
GC_Sphere_Center(i,1) = str2double(References{13,i});
end

GO = GC_Sphere_Center-Glenoid_Center;
HO = HC' - Glenoid_Center;
HO_overcorrected = HC_overcorrected' - Glenoid_Center;

%vector from glenoid sphere centre to glenoid centerline (perpendicular)
GHeccentricity = HO-dot(HO,GO/norm(GO))*(GO/norm(GO));
GHSI = norm(GHeccentricity) / (2*HHRadius)
%vector from glenoid sphere centre to glenoid centerline (perpendicular)
GHeccentricity_overcorrected = HO_overcorrected-dot(HO_overcorrected,GO/norm(GO))*(GO/norm(GO));
GHSI_overcorrected = norm(GHeccentricity_overcorrected) / (2*HHRadius)

fileID=fopen('Subluxation_calculation_after_surgery.txt','w');
fprintf(fileID,'%5s %15s %20s\n','Implant','Normal','Overcorrected');
fprintf(fileID,'%5s %15.3f %15.3f','GHSI',GHSI,GHSI_overcorrected);
fclose(fileID);
end
```

9 Appendix: Matlab code for the visualization of subluxation

In this script, a Matlab code is implemented for visualizing the subluxation. This code needs still improvements, it has been created just for a trial. The point x_pt, y_pt are the describing the coordinate system of the implant created in Abaqus. The idea is to try to plot the subluxation in the planes of the implant to have a better visualization of the posterioranterior and proximaldistal offsets. Therefore, all the obtained results are rotated from their original coordinate system to the implant's one and then plotted on the different axis.

```
clear all
close all

% Insert here the Radius used for the Humeral Head
HHRadius =24;

[GHSI, GHSI_overcorrected,SHSI ,SHSI_overcorrected, Glenoid_Center,GC_Sphere_Center,HC,HC_overcorrected]
= subluxation_calculation(HHRadius)

% Plot the subluxation
origin = [125.583717,24.282036,34.178317]';
x_pt = [124.213463,23.037871,33.420387]';
y_pt = [125.102044,22.287488,38.323241]';
x = (x_pt-origin)/norm(x_pt-origin);
y = (cross(x,(y_pt-origin)))/norm(cross(x,(y_pt-origin)));
z = cross(x,y);

rotation_matrix=[x,y,z]
HC_rotated=rotation_matrix*HC'
HC_overcorrected_rotated=rotation_matrix*HC_overcorrected'
Glenoid_Center_rotated=rotation_matrix*Glenoid_Center
GC_Sphere_Center_rotated=rotation_matrix*GC_Sphere_Center

figure
hold on
scatter(HC_rotated(1),HC_rotated(2))
scatter(HC_overcorrected_rotated(1),HC_overcorrected_rotated(2))
scatter(Glenoid_Center_rotated(1),Glenoid_Center_rotated(2))
scatter(GC_Sphere_Center_rotated(1),GC_Sphere_Center_rotated(2))
legend('HC','HC overcorrected','GC','GSC')
xlabel('x')
ylabel('y')

figure
hold on
scatter(HC_rotated(1),HC_rotated(3))
scatter(HC_overcorrected_rotated(1),HC_overcorrected_rotated(3))
scatter(Glenoid_Center_rotated(1),Glenoid_Center_rotated(3))
scatter(GC_Sphere_Center_rotated(1),GC_Sphere_Center_rotated(3))
legend('HC','HC overcorrected','GC','GSC')
xlabel('x')
ylabel('z')
figure

scatter3(HC(3),HC(2),HC(1))
hold on
scatter3(HC_overcorrected(3),HC_overcorrected(2),HC_overcorrected(1))
scatter3(Glenoid_Center(3),Glenoid_Center(2),Glenoid_Center(1))
scatter3(GC_Sphere_Center(3),GC_Sphere_Center(2),GC_Sphere_Center(1))
legend('HC','HC overcorrected','GC','GSC')
title('not rotated')
```